









INTERDISCIPLINARY PERSPECTIVE

Scalable low-cost seabed landers: the missing link for sustained, integrated, long-term observations in dynamic shallow seasArienne Calonge , Roeland Develter , Carlota Muñiz , Clea Parcerisas , Jan Reubens , Wieter Boone , Klaas Deneudt  & Elisabeth Debusschere 

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Introduction

Observing systems that generate repeated measurements over extended periods have been critical in detecting changes in oceanic conditions (Gould et al., 2013). Among the range of observational platforms (e.g. research vessels, towed instruments, and remotely operated vehicles), fixed platforms provide the highest temporal resolution and, when deployed in sufficient density, can also

Abstract

Shallow coastal seas are increasingly affected by accelerating climate change and widespread anthropogenic pressures, yet consistent, long-term monitoring data remain scarce and fragmented. Many existing observations are restricted to project-specific objectives, limiting their potential contribution to broader-scale assessments. Seabed landers, when equipped with a range of biotic and abiotic sensors, offer a non-invasive and cost-effective solution for ecosystem-scale monitoring of Essential Biodiversity Variables (EBVs) and Essential Ocean Variables (EOVs). Examples of EBVs and EOVs include marine mammal distribution, fish movement, underwater sound, plankton biomass and diversity, sea surface height, currents, and temperature. The integration of datasets improves our ability to address ecological questions across larger spatial and temporal scales. Incorporating biodiversity monitoring data into the Digital Twin of the Ocean, a high-resolution multi-dimensional virtual representation of the ocean, marks a critical step toward large-scale, standardized ecosystem-based assessments of ocean health. Strengthening infrastructure, data management capabilities, and protocols will further unlock the potential of seabed observatories to inform conservation efforts and policy development, particularly through the application of artificial intelligence. In this article, a perspective on the capacity of subsea observatories is presented, specifically on multi-purpose seabed landers, to deliver scalable, sustained, and high-resolution observations of EOVs and EBVs over large areas.

achieve improved spatial coverage across regions of interest (Von Jackowski, 2025). Developing innovative and strategic approaches within marine sensor networks enables sustained long-term, continuous observations required for informed policy making, marine spatial planning, and management.

Emerging autonomous technologies—devices capable of self-operation in remote environments for prolonged durations independent of any external control (Rodríguez

et al., 2012) demand an adaptable and cost-effective infrastructure design that can withstand the complexities of marine environments. Dynamic shallow seas are often characterized by extensive human activities (e.g. shipping, sand extraction, fishing, and development of offshore structures) and strong tidal currents (Hobohm et al., 2021; Kenny et al., 2018), creating complex conditions for observation and deployment. Although challenges persist, such as biofouling, sediment burial, entanglement, or collision risks posed by human activities, fixed platforms provide indispensable, low-logistics observations at scale for understanding the complexities of shallow seas.

Seabed landers are stationary observational platforms, typically constructed from a stainless or galvanized steel frame and deployed from vessels, designed to record a range of measurements at the seafloor over predetermined durations. State-of-the-art seabed landers are currently constrained by instrumentation and are often designed as large frames for single-purpose deployments. A scalable approach is to deploy low-cost observatories equipped with a suite of biotic and abiotic sensors capable of operating (semi-) continuously and autonomously (Fig. 1). This can include a variety of acoustic sensors (e.g. hydrophones and cetacean loggers), sonar systems, imaging devices, CTDs, environmental DNA (eDNA) samplers and oceanographic instruments, enabling the collection of

ecosystem-level data across multiple biological and physical parameters. Due to advances in battery technology that allow autonomous sensors to operate for longer periods, along with the miniaturization and decreasing cost of sensors (Moradian et al., 2025), scalable low-cost observation platforms have been more accessible and adaptable to a wide range of research needs of varying complexity.

Multi-purpose seabed landers contribute to higher quality data through the placement of sensors in a fixed position for the entire sampling period, minimizing disturbance from current-induced motion. Relative to self-floating systems attached to surface buoys or bottom-moorings, lander-mounted acoustic sensors offer remarkably improved detection efficiency and performance (Fischer et al., 2021; Goossens et al., 2020). Reduced noise in acoustic data is achieved when sensors are fixed—for example, as indicated by a lower number of lost minutes and negligible tilt angles in porpoise loggers (Fig. 2).

Compared to vessel operations, seabed landers provide a comprehensive and cost-effective approach to measure multiple complementary parameters of the marine ecosystem for extended periods of time. Wireless data transmission via acoustic or optical link is possible when landers are within the communication range of Uncrewed Surface Vehicles (USVs) or Autonomous Underwater Vehicles (AUVs) (Toma et al., 2023; Wang et al., 2020). Acoustic

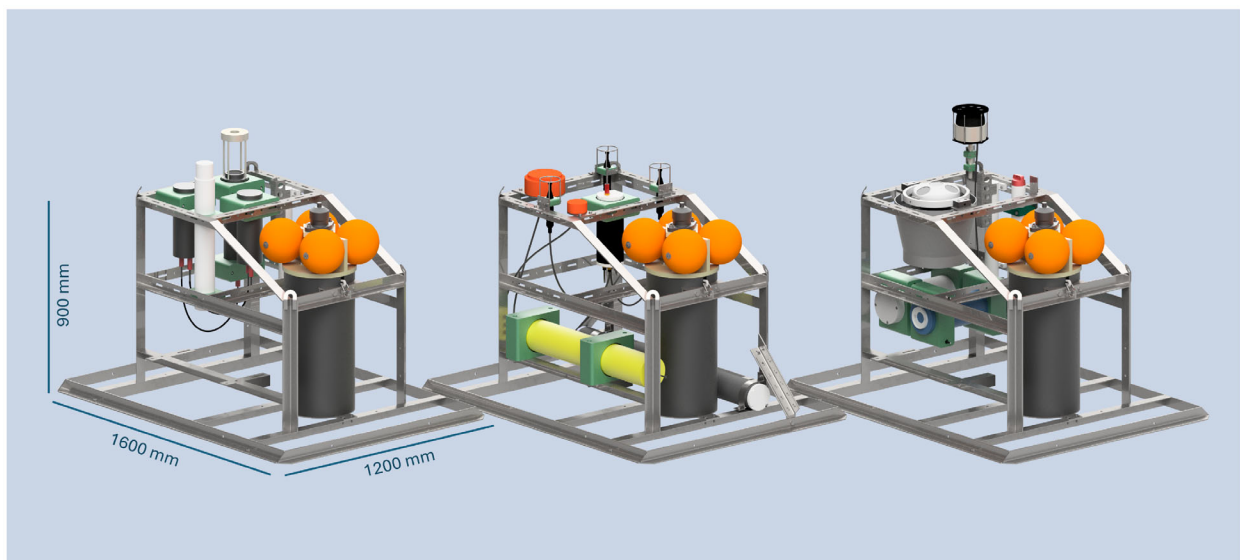


Figure 1. Three configurations of scalable low-cost seabed landers deployed in the Belgian part of the North Sea as part of the Belgian LifeWatch observatory. From left to right: plankton and biodiversity sensor suite with a continuous particle imaging and classification system, a porpoise logger and Conductivity, Temperature and Depth (CTD) sensor; acoustic sensor suite with an echosounder system: two split-beam transducers attached to an autonomous transceiver, and an acoustic recorder with up to four hydrophones; and an oceanographic sensor suite with seabed scanning sonar, current and waves (ADCP), CTD and a high-frequency pressure sensor. Each lander is equipped with an acoustic release that also serves as an acoustic receiver for biotelemetry. The lander's height design minimizes the loss of acoustic data from upward-facing transducers. Rendered from design files (available upon request).

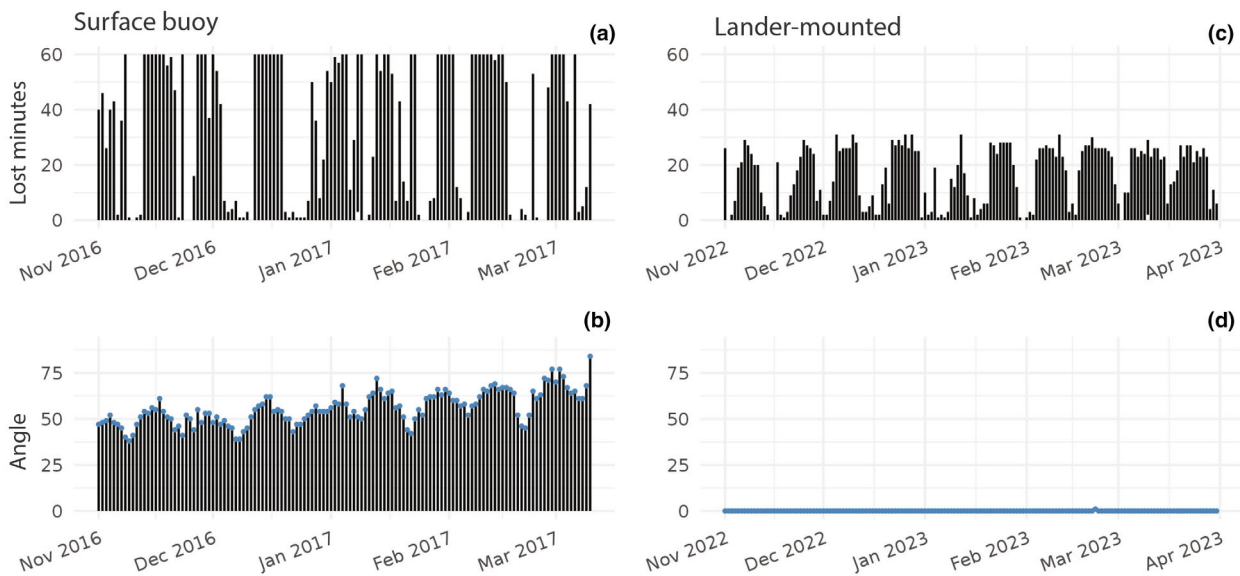


Figure 2. Comparison of the daily average lost minutes and daily range of angles obtained from surface- (a, b) and lander-mounted (c, d) C-PODs installed in a station of the Belgian Cetacean Passive Acoustic Network. Lost minutes refer to periods of excessive background noise, which can be related to tides, sediment transport, or the stability of the sensor. The C-POD was attached to a surface buoy at approximately 3 m below the sea surface until 2017. Due to chain and wave breaking noise, all C-PODs have been mounted on seabed landers since the summer of 2018.

release systems facilitate efficient deployment and recovery of landers, allowing ease of maintenance for optimal functionality. Landers equipped with remote sensors facilitate non-invasive observations of marine wildlife without interfering with their natural behaviors and habitats, which guarantees more accurate and ethical scientific observations. When multi-purpose seabed landers are strategically installed within a permanent network, beyond supporting a range of targeted research needs (e.g. academic studies and government- or internationally funded projects), long-term and broader scientific objectives can be addressed while reducing equipment, logistical, and maintenance costs (Reubens et al., 2019).

Building Capacities of Observatories in Ecosystem-Based Management

Shallow coastal seas have become subject to increasing cumulative pressures from anthropogenic activities and climate change (Kenny et al., 2018; Le Tixerant et al., 2010). Monitoring and gathering of useful information have become necessary to conduct knowledge-based and science-driven decisions. Such monitoring efforts could range from impact assessments of underwater noise from pile driving and shipping in the context of renewable energy development and offshore extractions (Slabbekoorn et al., 2010), electromagnetic fields from submarine cables and pipelines (Hutchison et al., 2020), coastal

developments on fish behavior and migration (Lowerre-Barbieri et al., 2019), commercial fishing on bycatch and habitat damage (Harris et al., 2022), to marine heatwaves on plankton dynamics (Meunier et al., 2025), among many others.

Ecosystem-based management centers ecosystem structure and functioning in resource management, recognizing that the components of the ecosystem are interconnected and interdependent (Curtin & Prellezo, 2010). Ecosystem-based management and impact assessments can benefit from large-scale autonomous multi-sensor observation networks that offer multiple spatio-temporally synchronous datasets (Fig. 3) (Calonge, Goossens, et al., 2024), providing simultaneous insights into multiple drivers and pressures on ecosystems. In contexts where data collection lacks methodological uniformity and is often fragmented, multi-purpose seabed landers provide an integrated approach through (semi-) continuous collection of high-resolution data across different components of the ecosystem. Consistency in data collection is essential to feed and validate ecological models that draw insights at broader ecosystem scales.

Data acquisition can differ between sensors according to their design and functionality, offering unique strengths and limitations that can be complementary when integrated to address specific research questions. For example, in studies of fish school dynamics, echosounders can provide detailed analyses of biomass and

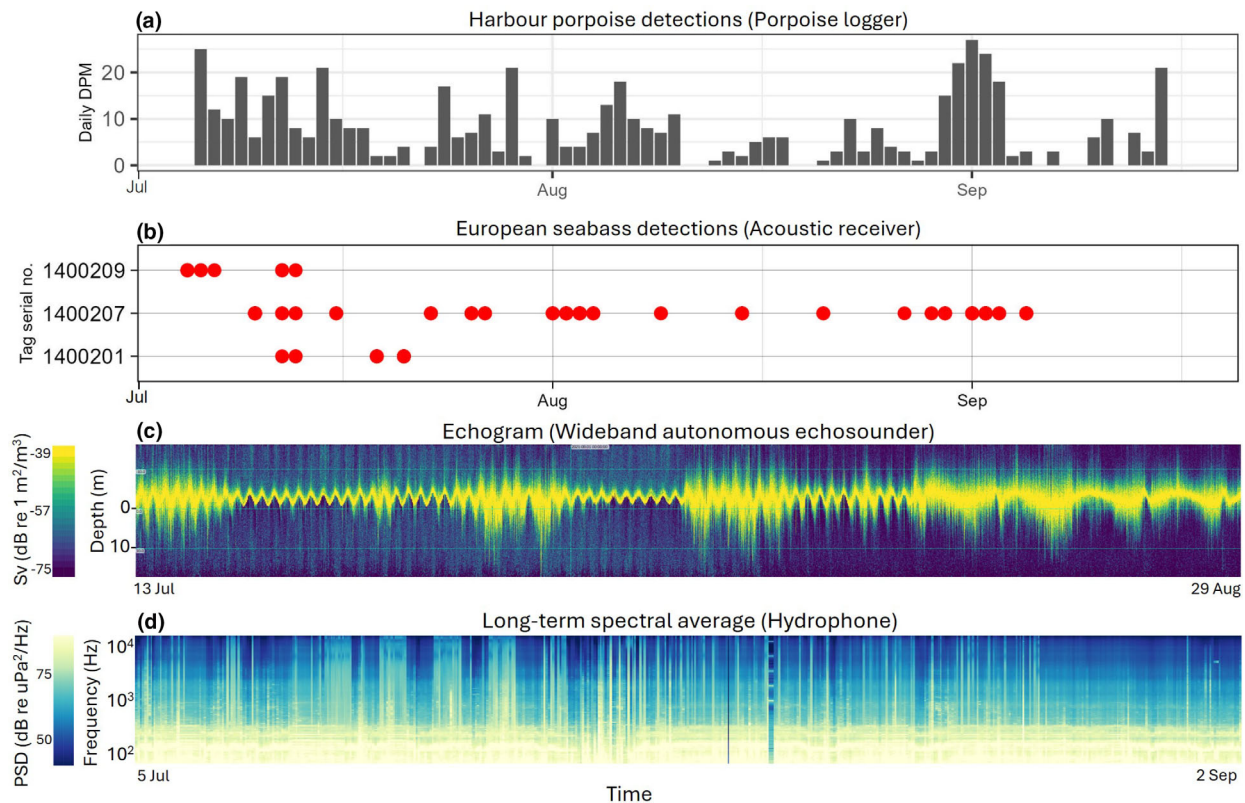


Figure 3. Example of data collected from one deployment of a scalable low-cost seabed lander from a station in the Belgian part of the North Sea from the 5th of July to the 17th of September 2021. The period of data collected by each sensor can differ, as indicated in the x-axis, due to varying memory or battery capacity. The lander was equipped with (a) a porpoise logger (C-POD, Chelonia) for harbor porpoise detection, shown here as Detection Positive Minutes (DPM) per day; (b) an acoustic receiver (Vemco, Innovasea) which detected three tagged European seabass individuals; (c) an autonomous echosounder with upward-facing split-beam transducers (70 and 200 kHz; WBAT, Simrad Kongsberg), with a compressed echogram showing here the volume backscattering strength (Sv), with yellow pixels in the echogram indicating the water surface; and (d) a hydrophone (Soundtrap ST300HF, Ocean Instruments), with the long-term spectral average (LTSA) displaying the change of sound pressure levels of median hourly hybrid millidecade bands audio signals over time (sampling frequency 48 kHz, FFT bins 48000, 50% overlap, Hann window, averaged at one-minute bins, then converted to dB).

schooling behavior but currently face limitations in species identification. Conversely, eDNA sampling enables species identification, yet lacks the capacity to assess schooling fish morphology and behavior. Passive acoustic monitoring (PAM) and acoustic telemetry (AT) have been extensively used to identify crucial habitats and study fine-scale animal behavior (Howe et al., 2019). PAM is restricted to detecting vocalizing species within a certain range, while AT only provides data on individuals that have been tagged (Calonge, Goossens, et al., 2024). Integrating multiple sensors into a single platform can effectively capture a broad spectrum of data, provided that potential sensor interference is minimized. Interference can occur when sensors with distinct operating mechanisms interact. For instance, the signals from an echosounder might occasionally affect the detection ability of

PAM or AT, particularly when their operational frequencies overlap.

Over the years, various projects have led to the deployment of numerous different sensors within the same environmental contexts, sometimes with overlapping objectives, resulting in multiple valuable subsea datasets (Bergès et al., 2019; SAMBAH, 2016; Scheidat et al., 2024). However, differences in sampling methodologies have limited integration. In contrast, standardized approaches to data collection, instead of project-specific protocols, enable the synthesis of datasets, offering a more comprehensive understanding of ecological patterns.

The practical value of multi-sensor observations has become increasingly evident in the recent years. Passive and active acoustic measurements, for example, have been used to monitor the presence and behavior of pelagic fish

when fish acoustic deterrent devices are used, using hydrophones and echosounders (Hubert et al., 2024), and to investigate predator–prey interactions using porpoise loggers and acoustic receivers (Calonge, Goossens, et al., 2024). Seafloor and surface-wave observations have also been applied to evaluate the long-term effectiveness of coastal nature-inclusive design (Boone et al., 2024). In this context, subsea observatories offer a promising platform to deliver integrated observations to support science-based management decisions, enabling a cost-effective collection of interoperable, reliable, and standardized information.

Open science, a technology-driven collaborative culture (Ramachandran et al., 2021), offers a paradigm for advancing multi-sensor observation networks. Implementing open data that is Findable, Accessible, Interoperable and Reusable (FAIR) within the scientific community and with the wider public, together with investments in innovative and collaborative infrastructures, expands research possibilities and accelerates scientific progress (Ramachandran et al., 2021). FAIR and open data principles alike prioritize findability and accessibility, but FAIR data extends these goals to interoperability, so that data can be integrated with other data workflows for analysis, and reusability, through metadata that supports replication across diverse contexts (Jati et al., 2022). Initiatives such as the European Open Science Cloud (EOSC), the EuropaBON monitoring database, EMODnet, and the Copernicus Marine Data Service foster an environment that promotes FAIR and open data, enabling the development of value-adding services from multiple sources of observation data (European Commission, 2025).

The pressing need to understand large-scale changes in ecosystems and how animal movement and behavior are impacted has already stimulated international collaborative efforts in developing observation networks. Recently, the European Tracking Network has developed and promoted an open protocol to standardize device compatibility between acoustic telemetry networks, thereby facilitating the detection of tagged animals across networks up to cross-continental scales (Aspillaga et al., 2024). A commitment to open science will not only foster long-term research opportunities, but will also enhance the overall value and effectiveness of large-scale multi-sensor observatories.

Numerous scientific studies and projects contributing to the implementation of several European Union (EU) directives could benefit from high-quality, long-term biodiversity datasets collected with multi-purpose seabed landers deployed at scale (<https://www.vliz.be/en/imis?module=ref&refid=392485>). Considering the case in the Belgian part of the North Sea, long-term datasets on the presence of cetaceans (Calonge, González, et al., 2024),

sound pressure levels (Flanders Marine Institute (VLIZ), 2021) and fish tracks (<https://europeantrackingnetwork.org/en>) have been foundational to knowledge-based products (Decrop, Deneudt, et al., 2025; Goossens et al., 2023; Parcerisas et al., 2024; Rumes et al., 2017; Verhelst et al., 2025) relevant to the EU Habitats Directive, Marine Strategy Framework Directive, and Common Fisheries Policy, respectively. Existing long-term biodiversity datasets have the potential to fill critical knowledge gaps in ecosystem dynamics, including species co-occurrence and interactions, multi-species hot-spots, habitat functionality, and distributional shifts driven by global and ecosystem-level changes (Fig. 3) (Calonge, Goossens, et al., 2024). Standardizing marine Essential Biodiversity Variables (EBVs), including species distribution, ecosystem structure and productivity, and community composition, will play a critical role in Marine Spatial Planning. EBVs, complementary to Essential Climate Variables, will be essential for meeting marine conservation and restoration targets both within the EU and globally, supporting the implementation of the European Green Deal, the EU Biodiversity Strategy for 2030, the European Restoration Law, and the Post-2020 Biodiversity Framework of the Convention on Biological Diversity.

The Future of Subsea Observatories

Observatories must increasingly serve as a hub of timely and accessible information, streamlining marine data services (She et al., 2016) (Fig. 4). Infrastructure and integration of remote observations must continuously improve to meet user needs in the growing blue economy. Long-term, continuous data series are essential in combating climate change, providing decades of observations and insights on environmental trends. A strategic vision for sensor networks, paired with robust data management capabilities, is critical to advancing transformative and systemic observation and forecasting systems capable of reliably detecting anomalies and extreme events. In that context, the project ‘Integration of biodiversity monitoring data into the Digital Twin Ocean’ (DTO-BioFlow) aims to expand the biodiversity component of the European Digital Twin Ocean, including new biodiversity data types (originating from acoustics, bio-logging, imaging, and genomics instruments) by improving interoperability and digitization of datasets, encouraging consolidated standards, quality control and harmonization of pipelines and data products. Such data are necessary to produce a consistent fine-scale multi-dimensional digital replica of marine biological processes to match with the capabilities of physico-chemical models.

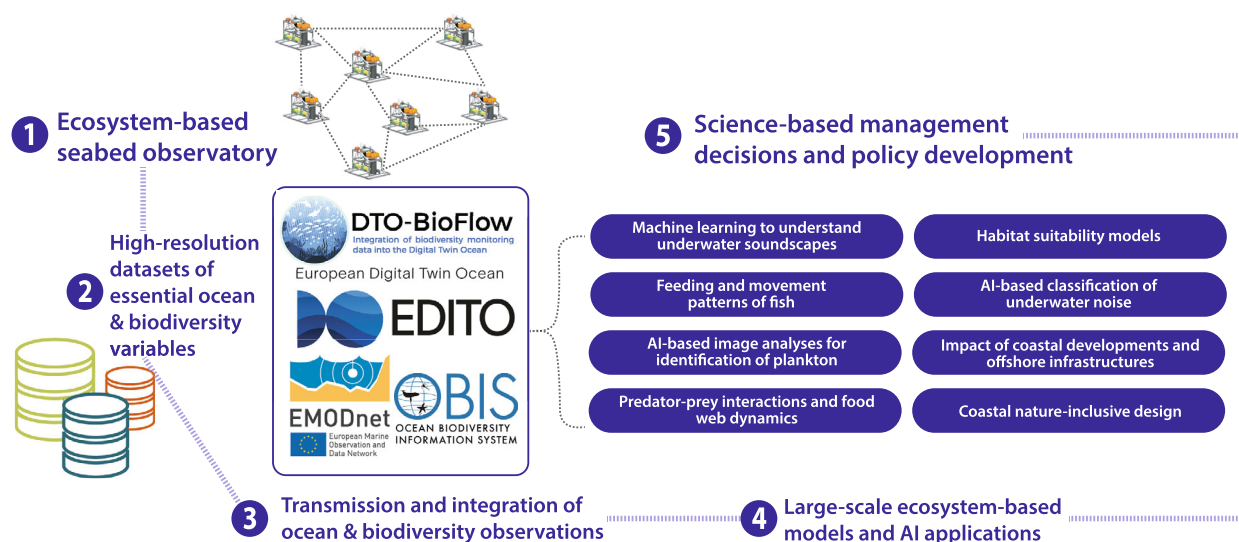


Figure 4. Ecosystem-based observatories produce high-resolution datasets of essential ocean and biodiversity variables. Datasets transmitted and integrated in public marine data platforms for large-scale ecosystem models and AI applications support timely science-based management decisions and policy development.

The long-term observations gathered through continuous deployments of autonomous sensors already serve the large training datasets required in developing artificial intelligence (AI) methods. Applications include machine learning for efficient segregation and labeling of potential biological sounds (Parcerisas et al., 2024), predictions of species-specific habitat selection by applying machine learning to acoustic telemetry datasets (Griffin et al., 2021), AI-based classifications of underwater vessel noise and plankton (Azmi et al., 2025; Decrop, Deneudt, et al., 2025; Decrop, Lagaisse, et al., 2025), and acoustic fish species echo classification (Yassir et al., 2023). Establishing edge computing incorporated with fast-growing AI methods would further strengthen ecosystem monitoring for adequate response.

The future of autonomous observatories lies in reducing data latency and increasing autonomy, which can be achieved through in situ preprocessing of sensor data thus reducing data transmission or autonomous data offloading. Optimization of measurements through inter-sensor connectivity and intelligent triggering enabling adaptive sampling will advance an observatory's autonomy. Coupled autonomous observations and AI will support the efficient transmission of biodiversity data, benefiting ecosystem models.

Conclusion

The practicality of multi-purpose seabed landers is evident in generating high-quality long-term observations in shallow coastal seas. However, adaptable infrastructure

design is only one component of a broader integrative framework necessary for a long-term implementation. Sustaining and expanding existing observation networks also requires stronger collaboration among countries and research institutions. Cross-disciplinary scientific workshops, shared infrastructure and expertise, adherence to standardized protocols, and a strong commitment to open science are all essential. Such collaborative efforts will extend the relevance of observational data beyond project-specific objectives and timelines, allowing integration into broader ecological assessments that benefit both science and policy.

Collaboration will also minimize redundancy in sampling efforts and will foster methodological innovation and affordability. The value of biodiversity data platforms, such as EMODnet (<https://emodnet.ec.europa.eu/en>), OBIS (obis.org), and the EU DTO, can be fully realized through coordinated, evidence-based decision-making that prioritizes ecosystem health and ensures their effective integration into environmental management. Continued support from the research community and appropriate long-term funding are crucial to maintaining and advancing these platforms, which are foundational for large-scale ecosystem monitoring and management.

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Author Contributions

Arienne Calonge: Investigation; writing – original draft; writing – review and editing; visualization; validation; data curation; formal analysis. **Roeland Develter:** Writing – original draft; writing – review and editing; visualization; investigation; validation; methodology. **Carlota Muñiz:** Writing – review and editing; investigation; project administration; supervision; methodology. **Clea Parcerisas:** Investigation; visualization; writing – review and editing. **Jan Reubens:** Investigation; writing – review and editing; project administration; supervision; methodology. **Wieter Boone:** Supervision; writing – review and editing; investigation. **Klaas Deneudt:** Writing – review and editing; project administration; resources; supervision; funding acquisition. **Elisabeth Debusschere:** Conceptualization; project administration; supervision; investigation; writing – review and editing; methodology.

Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

The datasets supporting the contents of this manuscript are available in the Integrated Marine Information System (<https://www.vliz.be/en/imis?module=ref&refid=392485>). Biotelemetry and C-POD datasets are openly available in the Lifewatch data explorer (<https://rshiny.vsc.lifewatch.be/etn-data/>), and the passive acoustic recording data from SoundLib (<http://marinesoundlib.org/>). Echosounder data can be made available upon request.

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